

GENERATION OF SPREAD-SPECTRUM MULTIPLE ACCESS CODES
WITH ZERO-CORRELATION WINDOWS

5 The present application is a continuation-in-part of, and claims priority under 35 U.S.C. §§ 120 and 365(c) to co-pending PCT application PCT/CN00/00179, filed June 26, 2000, designating multiple countries including the United States, but was not published in English under PCT Article 21(2).

10 Related Applications

The present application is related to PCT application bearing PCT/CN00/00092, filed April 18, 2000, and co-pending United States patent application entitled “Spread Spectrum Multiple Access Codes and Code Groups Generated by Rotation Transformation,” filed herewith and bearing attorney docket number 10748-0003-999. The 15 aforementioned United States patent application is hereby incorporated by reference in its entirety.

Field of the Invention

20 The present invention relates generally to spread spectrum technology and digital mobile communication technology. More particularly, the present invention relates to the generation of spread-spectrum multiple access codes with desirable non-periodic auto-correlation and cross-correlation functions.

Background of the Invention

25 A wireless communication channel is typically a time-varying channel that is affected by many random factors such as angle, frequency (produced by Doppler frequency spread), and time (produced by multi-path propagation) dispersion. Random angle dispersion causes signals at different receiving points to fluctuate randomly (i.e., spatial-selective fading). Random frequency dispersion causes received signals to fluctuate 30 randomly with time (i.e., time-selective fading). Random time dispersion causes different frequency spectrum components of a received signal to fluctuate randomly (i.e., frequency-selective fading). Spatial-selective, time-selective and frequency-selective fading all significantly deteriorate the performance and capacity of the wireless communication channel.

One approach to overcoming the problem of fading is by using diversity reception. In general, diversity reception refers to techniques for improving the Signal-to-Noise Ratio (SNR) of a communication channel by suitably combining a number of signal transmission paths that carry the same information but have uncorrelated fading. In digital wireless spread spectrum communication systems, it is advantageous to use high quality spread spectrum codes (e.g., codes that have desirable auto-correlation and cross-correlation characteristics, etc.) to take full advantage of diversity reception.

5 In the prior art, most high quality spread spectrum codes and code groups were found by computer searches. Computer searching, however, is costly, time consuming and 10 does not always produce the desired high quality spread spectrum codes or code groups.

In view of the foregoing, there exists a need for a method of generating high quality spread spectrum codes and code groups.

15 Summary of the Invention

An embodiment of the present invention is a method of constructing an orthogonal group of spread spectrum multiple access codes each having a non-periodic auto-correlation function that has no side-lobe within a predefined window. The width of the predefined window may be varied according to practical requirements. Some non-periodic cross-20 correlation side lobe values may not be exactly zero within the predefined window. Nevertheless, the cross-correlation side lobe values are so small that they are practically negligible.

According to an embodiment of the present invention, the method of constructing an 25 orthogonal group of spread spectrum multiple access codes includes the following steps:

- Select an N -bit spread spectrum code with an ideal periodic auto-correlation function.
- Transform the selected spread spectrum code using orthogonal rotation to form an orthogonal group of spread spectrum codes. This group contains N spread spectrum codes 30 that are completely orthogonal with respect to each other.
- Extend each of the N spread spectrum codes produced in the transformation step by 2Δ elements to form a group of spread spectrum codes each having $N+2\Delta$ elements, where Δ denotes a predefined width of the zero-correlation window of the non-periodic auto-correlation function of the spread spectrum codes. In one embodiment, each one of the N

spread spectrum codes may be extended by appending Δ elements at the beginning of the sequence and by appending Δ elements at the end.

- Evaluate the non-periodic cross-correlation functions of all the spread spectrum codes of the group.
- Select the spread spectrum codes with the smallest cross-correlation functions to 5 form a new group of spread spectrum codes.

The new group of spread spectrum codes may be used for the spreading operation in a spread spectrum communication system. The same orthogonal group of spread spectrum codes may be used for de-spreading operations at the receiver, after removing the beginning 10 Δ elements and the ending Δ elements from each sequence by setting them to zero.

Some advantages of the present invention include:

- The present invention transforms the problem of searching for a spread spectrum multiple access code that has a non-periodic correlation function with a zero-correlation 15 window into the simpler problem of searching for a spread spectrum multiple access code that has an ideal periodic correlation function. It thereby simplifies the searching method and extends the searching scope.
- The properties of the orthogonal group of spread spectrum codes provided by embodiment(s) of the present invention are substantially independent of the original phase 20 of each spread spectrum code. More precisely, the auto-correlation function of each spread spectrum code is totally independent of its original phase, and for the cross-correlation function, only a fixed phase shift is introduced. As a result, communication channels encoded with the spread spectrum codes can withstand to some extent Doppler frequency shifts and channel phase swings.

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Brief Description of the Drawings

For a better understanding of the invention, reference should be made to the following detailed description taken in conjunction with the accompanying drawings, in which:

30 Fig. 1A depicts a non-periodic auto-correlation function and its zero-correlation window of a spread spectrum multiple access code.

Fig. 1B depicts a non-periodic cross-correlation function and its zero-correlation window between two spread spectrum multiple access codes.

35 Fig. 2 depicts an extended code sequence according to one embodiment of the present invention.

Fig. 3 is a block diagram of a transmitter device according to one embodiment of the present invention.

Fig. 4 is a block diagram of a transmitter device according to another embodiment of the present invention.

Fig. 5 is a block diagram of a receiver device according to one embodiment of the

5 present invention.

Fig. 6 is a block diagram of a receiver device according to another embodiment of the present invention.

Description of the Preferred Embodiments

10 As used herein, a non-periodic auto-correlation function of a spread spectrum code, $\mathbf{b} = [b_0, b_1, b_2, \dots, b_{N-1}]$, is determined by:

$$r_b(k) = \frac{1}{\|\mathbf{b}\|^2} \sum_{n=0}^{N-1} b_n b^*_{n+k} \quad (1)$$

15 where b^* denotes the complex conjugate of b and where

$$\|\mathbf{b}\|^2 \equiv \sum_{n=0}^{N-1} b_n b^*_{n} \quad (2)$$

20 In the prior art, an ideal spread spectrum code is defined to be a spread spectrum code with a non-periodic auto-correlation function that is zero everywhere except at the origin; in other words, the ideal spread spectrum code has no side-lobe. In the prior art, an ideal spread spectrum code group is defined to be a group of spread spectrum codes where
25 all the codes have no side-lobe and every non-periodic cross-correlation function of the group must be zero everywhere. Unfortunately, theoretical studies and computer searches show that such ideal spread spectrum codes and code groups do not exist under the complex number field.

30 In PCT application bearing application number PCT/CN00/00028, entitled: "Coding Method for Spread Spectrum Multiple Access Code with Zero Correlation Window," the inventor herein pointed out that the requirements for ideal spread spectrum multiple access codes can be relaxed when bi-directional synchronization is applied. The relaxed requirements are as follows:

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- The side-lobe values for the non-periodic auto-correlation functions of spread spectrum multiple access codes do not need to be zero everywhere. The side-lobe values need to be zero only within a window $(-\Delta, \Delta)$, where Δ represents the sum of the maximum time dispersion and the maximum timing error of the communication channel where the spread spectrum multiple access codes are used. The non-periodic auto-correlation function 100 of a spread spectrum multiple access code is illustrated in Fig. 1A. As shown, the non-periodic auto-correlation function 100 has a zero-correlation window within which the function is zero or close to zero.
- The non-periodic cross-correlation functions of the spread spectrum multiple access codes do not need to be zero everywhere. The non-periodic cross-correlation functions of the spread spectrum multiple access codes need to be zero, or close to zero, only within the window $(-\Delta, \Delta)$. The non-periodic cross-correlation function 110 between two spread spectrum multiple access code is illustrated in Fig. 1B. As shown, the non-periodic cross-correlation function 110 has a zero-correlation window within which the function is zero or close to zero.

In PCT Application bearing application number PCT/CN00/00092, entitled "Orthogonal Transformation Method for Spread Spectrum Multiple Access Coding," and co-pending United States patent application entitled "Spread Spectrum Multiple Access Codes and Code Groups Generated by Rotation Transformation," the inventor herein

20 disclosed a method of transforming a initial spread spectrum code to an orthogonal group of spread spectrum access codes. A significant characteristic of that transformation method is that, after applying multiple orthogonal rotation transformations, the resulting codes remain orthogonal to each other. In addition, the auto-correlation function of each of the resulting codes is substantially consistent with that of the initial spread spectrum code, except for a

25 small amount of fixed phase shift.

In addition to inventing the subject matter disclosed in the above-mentioned PCT applications, the inventor herein has henceforth invented the subject matter of the present application. In one embodiment, the present invention provides a novel method of 30 generating a group of spread-spectrum multiple access codes each having a non-periodic auto-correlation function with a zero-correlation window. Furthermore, the cross-correlation functions of the spread-spectrum multiple access codes are almost zero. The spread-spectrum multiple access codes generated can thus be considered “ideal” under the relaxed requirements.

In particular, according to one embodiment of the present invention, the method includes the following steps:

Step 1

5 Select a spread spectrum code with an ideal periodic auto-correlation function and a length of N :

$$\mathbf{b} = [b_0, b_1, b_2, \dots, b_{N-2}, b_{N-1}]$$

10 In the present discussion, an ideal periodic auto-correlation function refers to:

$$\begin{aligned} \mathbf{r}_b(k) &= \frac{1}{\|\mathbf{b}\|^2} \sum_{n=0}^{N-1} b_n b^*_{(n+k) \bmod N}, \quad |k| \leq N \quad (3) \\ 15 &= \begin{cases} 1 & k = 0 \\ 0 & k \neq 0 \end{cases} \end{aligned}$$

where $\bmod N$ denotes a modular N operation, where b^* is the complex conjugate of b ; and

$$20 \quad \|\mathbf{b}\|^2 \equiv \sum_{n=0}^{N-1} b_n b^*_{(n+k) \bmod N} \quad (4)$$

25 Note that, according to equation (3) above, the n -th bit of the code \mathbf{b} is multiplied by the $((n+k) \bmod N)$ -th bit of the complex conjugate \mathbf{b}^* . For example, if $N = 4$, and if $k = 1$, then when $n = 3$, $(n+k) \bmod N = 0$, and

$$r_b(1) = b_0 \times b_1 + b_1 \times b_2 + b_2 \times b_3 + b_3 \times b_0$$

30 An example of a spread spectrum code with an ideal periodic auto-correlation function is the broadcast spread spectrum code of the Large Area Synchronous CDMA system (LAS-CDMA), which is a proprietary technology of LinkAir Communications, Inc. Additional information about the LAS-CDMA technology can be found on the World Wide Web at the URL address: www.linkair.com.

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The broadcast spread spectrum code of LAS-CDMA is a ternary sequence s_0 with twenty-one elements in length:

$$s_0 = [+ + + + + - + 0 + 0 - + + - 0 0 + - 0 - -]$$

It can be easily verified that the periodic auto-correlation function of this ternary sequence is ideal. It can also be verified that any cyclically shifted version of sequence s_0 also has a perfectly ideal periodic auto-correlation function.

Step 2

Apply an orthogonal rotation transformation on \mathbf{b}_0 to form a group of spread spectrum codes, $\{\mathbf{b}_0, \mathbf{b}_1, \dots, \mathbf{b}_{N-1}\}$. The group has N spread spectrum codes that are completely orthogonal to each other. The N spread spectrum codes are:

$$\mathbf{b}_0 = [b_0, b_1, b_2, \dots, b_{N-2}, b_{N-1}]$$

$$\mathbf{b}_1 = [b_0, b_1 e^{j\Delta\varphi}, b_2 e^{j2\Delta\varphi}, \dots, b_{N-2} e^{j(N-2)\Delta\varphi}, b_{N-1} e^{j(N-1)\Delta\varphi}]$$

$$15 \quad \mathbf{b}_2 = [b_0, b_1 e^{j2\Delta\varphi}, b_2 e^{j4\Delta\varphi}, \dots, b_{N-2} e^{j2(N-2)\Delta\varphi}, b_{N-1} e^{j2(N-1)\Delta\varphi}]$$

...

$$\mathbf{b}_k = [b_0, b_1 e^{jk\Delta\varphi}, b_2 e^{j2k\Delta\varphi}, \dots, b_{N-2} e^{jk(N-2)\Delta\varphi}, b_{N-1} e^{jk(N-1)\Delta\varphi}]$$

$$20 \quad \mathbf{b}_{N-1} = [b_0, b_1 e^{j(N-1)\Delta\varphi}, b_2 e^{j2(N-1)\Delta\varphi}, \dots, b_{N-2} e^{j(N-1)(N-2)\Delta\varphi}, b_{N-1} e^{j(N-1)(N-1)\Delta\varphi}]$$

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where $\Delta\varphi = \frac{2\pi}{N}$. Orthogonal rotation transformation is described in detail in the above

25 referenced patent co-pending U.S. patent application and PCT application
PCT/CN00/00092.

Any one of the sequences \mathbf{b}_l ($l = 0, 1, \dots, N - 1$) generated by the orthogonal rotation transformation has an ideal periodic auto-correlation function. The relative rotations between any two sequences are integral periods, and every pair of sequences is orthogonal to each other. Therefore, N mutually orthogonal sequences with an ideal periodic auto-correlation function will result from an orthogonal rotation transformation of a sequence with an ideal periodic auto-correlation function.

Step 3

Extend the length of each sequence \mathbf{b}_l ($l = 0, 1, \dots, N - 1$) in the mutually orthogonal group by 2Δ elements to form a new set of sequences \mathbf{a}_l ($l = 0, 1, \dots, N - 1$) each having a length of $N+2\Delta$ elements. In the present embodiment, Δ represents the desired width of the zero correlation window, which generally corresponds to the maximum tolerance of the communication system in which the codes are used. In some embodiments, the desired width of the zero correlation window is the sum of the maximum time dispersion and the maximum timing error of a communication channel of the communication system.

The new sequences are as follows:

10 $\mathbf{a}_0 = [b_{N-\Delta+1}, b_{N-\Delta+2}, \dots, b_{N-1}, b_0, b_1, b_2, \dots, b_{N-2}, b_{N-1}, b_0, b_1, \dots, b_{\Delta-1}]$

\vdots

$\mathbf{a}_l = [b_{N-\Delta+1} e^{j(N-\Delta+1)l\Delta\phi}, b_{N-\Delta+2} e^{j(N-\Delta+2)l\Delta\phi}, \dots, b_{N-1} e^{j(N-1)l\Delta\phi},$
 $b_0, b_1 e^{jl\Delta\phi}, b_2 e^{j2l\Delta\phi}, \dots, b_{N-2} e^{j(N-2)l\Delta\phi}, b_{N-1} e^{j(N-1)l\Delta\phi},$
15 $b_0, b_1 e^{jl\Delta\phi}, \dots, b_{\Delta-1} e^{j(\Delta-1)l\Delta\phi}]$

where $l = 0, 1, \dots, N - 1$.

20 As shown, the first Δ elements of each of the new sequences \mathbf{a}_l ($l = 0, 1, \dots, N - 1$) are the last Δ elements of the original sequences \mathbf{b}_l ($l = 0, 1, \dots, N - 1$), and the last Δ elements of the new sequences \mathbf{a}_l ($l = 0, 1, \dots, N - 1$) are the first Δ elements of the original sequences \mathbf{b}_l ($l = 0, 1, \dots, N - 1$). The middle N elements of the new sequences \mathbf{a}_l ($l = 0, 1, \dots, N - 1$) are the original sequences \mathbf{b}_l ($l = 0, 1, \dots, N - 1$).

25 Consider the broadcast spread spectrum code of LAS-CDMA as an example. As mentioned above, the broadcast spread spectrum code of LAS-CDMA is a ternary sequence \mathbf{s}_0 with a length of twenty-one elements:

30 $\mathbf{s}_0 = [+ + + + - + 0 + 0 - + + - 00 + - 0 - -]$

Suppose the desired width of the zero-correlation window is four ($\Delta = 4$). Then \mathbf{a}_0 should be:

$\mathbf{a}_0 = [-0 - - + + + + - + 0 + 0 - + + - 00 + - 0 - - + + + +]$

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As illustrated in Fig. 2, the first four elements of a_0 are [- 0 - -] and the last four elements of a_0 are [+ + + +]. The first four elements of a_0 correspond to the last four elements of s_0 , and the last four elements of a_0 correspond to the first four elements of s_0 .

Observe that, when $k < \Delta$, the non-periodic auto-correlation of \mathbf{a}_l ($l = 0, 1, \dots, N - 1$) 5 is the periodic auto-correlation of \mathbf{b}_l . Furthermore, the non-periodic cross-correlation function between \mathbf{b}_l and \mathbf{a}_l ($l = 0, 1, \dots, N - 1$) is the periodic auto-correlation function of \mathbf{b}_l . Here, the beginning Δ elements and ending Δ elements of \mathbf{a}_l ensure that the width of zero correlation window is $(-\Delta, \Delta)$. The actual spread spectrum function is provided by the N elements in the middle.

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Step 4

Some of the spread spectrum codes generated the present embodiment may have undesirable cross-correlation functions. Thus, the present embodiment may include the steps of evaluating all non-periodic cross-correlation functions between \mathbf{b}_l and $\mathbf{a}_{l'}$ ($l, l' = 15 0, 1, \dots, N - 1, l \neq l'$) and selecting N_0 spread spectrum codes that have smaller non-periodic cross-correlation functions from among all non-periodic cross-correlation functions between \mathbf{b}_l and $\mathbf{a}_{l'}$ ($l, l' = 0, 1, \dots, N - 1, l \neq l'$). The number of spread spectrum codes selected depends on various factors including the tolerance of the communication system, the number of codes needed, etc. In this embodiment, the selected spread spectrum codes are $\{\mathbf{b}_m\}$ and 20 $\{\mathbf{a}_m\}$, ($m = 0, 1, \dots, N_0 - 1$). The remaining unselected spread spectrum codes with undesirable cross-correlation functions are discarded.

In some embodiments of the present invention, step 4 can be omitted. In those 25 embodiments, none of the spread spectrum codes is discarded, and the code groups $\{\mathbf{b}_m\}$ and $\{\mathbf{a}_m\}$ include the entire sets of \mathbf{b}_l and \mathbf{a}_l .

The newly generated code group $\{\mathbf{a}_m\}$ is a group of spread spectrum codes that can be used for the spreading operations in a transmitting device. In a receiving device, the corresponding $\{\mathbf{b}_m\}$, which is the middle part of $\{\mathbf{a}_m\}$ after removing the beginning Δ 30 elements and ending Δ elements respectively, can be used for the de-spreading operations.

Code groups generated according to embodiments of the present invention can be used in a wide variety of communication systems. Fig. 3 depicts a block diagram of a transmitter 300 for a wireless communication system according to an embodiment of the 35 present invention. The transmitter 300 may be implemented as part of a base station or a

mobile unit. As depicted, transmitter 300 includes a code generator 310 that stores a predetermined spread spectrum code $[b_0, b_1, b_2, \dots, b_{N-1}]$ (312) and a set of predetermined basic rotation angles $\Delta\varphi, 2\Delta\varphi, 3\Delta\varphi, \dots, (N-1)\Delta\varphi$ (314). In this embodiment, the predetermined spread spectrum code 312 has an ideal periodic auto-correlation function. That is, the code 312 has no side-lobe. Using the predetermined code 312, the predetermined basic rotation angles, the code generator 310 generates a code b_l that includes the following elements:

$$b_0, b_1 e^{jl\Delta\varphi}, \dots, b_{N-1} e^{j(N-1)l\Delta\varphi}$$

10 The code b_l is then extended by a predetermined number (Δ) of elements by a code extension unit 315 to produce a code \mathbf{a}_l , where

$$\mathbf{a}_l = [b_{N-\Delta+1} e^{j(N-\Delta+1)l\Delta\varphi}, b_{N-\Delta+2} e^{j(N-\Delta+2)l\Delta\varphi}, \dots, b_{N-1} e^{j(N-1)l\Delta\varphi}, \\ b_0, b_1 e^{jl\Delta\varphi}, b_2 e^{j2l\Delta\varphi}, \dots, b_{N-2} e^{j(N-2)l\Delta\varphi}, b_{N-1} e^{j(N-1)l\Delta\varphi}, \\ b_0, b_1 e^{jl\Delta\varphi}, \dots, b_{\Delta-1} e^{j(\Delta-1)l\Delta\varphi}]$$

15 In the present implementation, the code extension unit 315 includes logic for transposing the first Δ elements and the last Δ elements of the code b_l , respectively, to the beginning and end of the extended code \mathbf{a}_l .

With reference still to Fig. 3, The extended code \mathbf{a}_l is then provided to a spreader circuit 320, which uses the code \mathbf{a}_l to spread the data to be transmitted. The spreaded data is then filtered by filter 330 and modulated by a carrier frequency 340. The modulated data is then filtered, amplified and transmitted via antenna 370. Note that the transmitter 300 of Fig. 3 depicts a simplified example of a wireless transmitter configuration that is well known in the art. Many other configurations consistent with the scope and principles of the present invention are also possible.

30 Fig. 4 depicts a simplified block diagram of a transmitter 400 for a wireless communication system according to another embodiment of the present invention. The transmitter 400 does not use a code generator for generating the codes. Rather, the transmitter 400 uses a memory 410 having stored therein a group of extended spread spectrum multiple access codes (412) that is generated according to an embodiment of the

present invention disclosed above. Selection signals can be used to select a particular one of the codes of the code groups to be used by the transmitter 400 to spread the data to be transmitted.

Fig. 5 depicts a block diagram of a receiver 500 for a wireless communication system according to an embodiment of the present invention. The receiver 500 may be used to receive data transmitted by transmitter 300 or 400, and may be implemented as part of a base station or a mobile station of the communication system. In Fig. 5, a despreading code is generated by a code generator according to the predetermined spread spectrum code $[b_0, b_1, b_2, \dots, b_{N-1}]$ (312) and the set of predetermined basic rotation angles $\Delta\varphi, 2\Delta\varphi, 3\Delta\varphi, \dots, (N-1)\Delta\varphi$ (314). The despreading code thus generated is used by a despreader 510 to de-spread received data. According to the present embodiment, the received data is spread by a code \mathbf{a}_l , where

$$\mathbf{a}_l = [b_{N-\Delta+1} e^{j(N-\Delta+1)l\Delta\varphi}, b_{N-\Delta+2} e^{j(N-\Delta+2)l\Delta\varphi}, \dots, b_{N-1} e^{j(N-1)l\Delta\varphi}, b_0, b_1 e^{jl\Delta\varphi}, b_2 e^{j2l\Delta\varphi}, \dots, b_{N-2} e^{j(N-2)l\Delta\varphi}, b_{N-1} e^{j(N-1)l\Delta\varphi}, b_0, b_1 e^{jl\Delta\varphi}, \dots, b_{\Delta-1} e^{j(\Delta-1)l\Delta\varphi}]$$

A code $\mathbf{b}_l = [b_0, b_1 e^{jl\Delta\varphi}, \dots, b_{N-1} e^{j(N-1)l\Delta\varphi}]$ can be used for despreading the received data.

Fig. 6 depicts a block diagram of a receiver 600 for a wireless communication system according to another embodiment of the present invention. The receiver 600 may be used to receive data transmitted by transmitter 300 or 400, and may be implemented as part of a base station or a mobile station of the communication system. A code group 412 is stored in a memory unit 410 of the receiver 600. In Fig. 6, a code \mathbf{b}_l , which is one of the codes stored in the memory unit 410, is selected and used to despread received data. Again, in this embodiment, the selected code corresponds to the spreading code used by the transmitter.

The foregoing description, for purposes of explanation, used specific nomenclature to provide a thorough understanding of the invention. However, it will be apparent to one skilled in the art that the specific details are not required in order to practice the invention. In other instances, well known circuits and devices are shown in block diagram form in

order to avoid unnecessary distraction from the underlying invention. Thus, the foregoing descriptions of specific embodiments of the present invention are presented for purposes of illustration and description. They are not intended to be exhaustive or to limit the invention to the precise forms disclosed, obviously many modifications and variations are possible in view of the above teachings. The embodiments were chosen and described to best explain 5 the principles of the invention and its practical applications, to thereby enable others skilled in the art to best utilize the invention and various embodiments with various modifications as are suited to the particular use contemplated.

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